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HCMM ENERGY BUDGET DATA AS A MODEL INPUT FOR ASSESSING  
REGIONS OF HIGH POTENTIAL GROUNDWATER POLLUTION

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ABSTRACT

A field study was conducted in a barley [*Hordeum vulgare* L.] canopy to assess the potential for extracting canopy temperature information from radiometric measurements at incomplete cover. Composite temperatures consisting of emitted and reflected longwave radiation from the barley and the soil background were measured by a nadir-viewing infrared radiometer. Canopy temperatures were measured by an infrared radiometer at a 30° angle from the horizontal. Soil temperatures were measured with thermocouples.

Composite temperatures were 0.5 to 11.5 C higher than canopy temperatures with the largest difference occurring at low canopy cover. The correlation between composite and canopy temperature for data acquired throughout the growing season was not significant. An equation which considered emitted radiation from both the canopy and the soil background, and which included reflected sky radiance was used to predict crop temperatures from nadir measurements. Predicted temperatures agreed with observed values ( $r^2 = 0.88$ ), and the prediction accuracy was independent of canopy cover. When emissivity corrections were not applied, prediction accuracy varied with percent cover with largest errors occurring at low cover. Prediction accuracy also varied with canopy cover when appropriate emissivities were used but sky radiance was ignored. Results indicate that canopy temperatures can be estimated from nadir measurements at incomplete cover if percent cover, soil temperature, and sky radiance are known.

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Additional index words: Emissivity, remote sensing, radiometry, radiance, longwave radiation.

## INTRODUCTION

2 Remotely-sensed surface temperatures can be useful for many  
3 agricultural applications including evapotranspiration modeling (Brown  
4 and Rosenberg, 1973; Stone and Horton, 1974; Heilman and Kanemasu, 1976;  
5 Soer, 1980), soil moisture detection (Idso et al., 1975; Idso and  
6 Ehrler, 1976; Schmugge et al., 1978; Heilman and Moore, 1980), plant  
7 stress detection (Wiegand and Namken, 1966; Jackson et al., 1977; Ehrler  
8 et al., 1978), yield prediction (Idso et al., 1977; Idso et al., 1979)  
9 and irrigation scheduling (Jackson et al., 1977). Most studies which  
10 have used remote measurements have been restricted to bare soils or  
11 fully developed crop canopies because of the complexities involved in  
12 interpreting thermal data at less than full cover.

13 Much of the complexity results because the remote sensing  
14 instrument measures emitted and reflected radiation from vegetation and  
15 soil differing in temperature and emissivity. Hatfield (1979) reported  
16 that differences between angular and vertical infrared thermometer  
17 measurements of canopy temperatures were greatest at 20 to 50% cover and  
18 decreased as canopy density increased. He speculated that differences  
19 were enhanced by emissivity variations. Millard et al. (1980) found  
20 that for canopies covering at least 85% of the soil surface, airborne  
21 measurements of plant temperatures differed from ground measurements by  
22 less than 2 C. At 50% cover, differences were as large as 9 C.  
23 Investigators have shown that even at full cover thermal radiance from  
24 the soil surface can affect remote temperature measurements of crop  
25 canopies (Blad and Rosenberg, 1976).

26 Incomplete plant canopies are important remote sensing targets  
27 because of the potential benefits arising from early assessment of crop

1 condition. Jackson et al. (1979) presented a model for extracting crop  
2 temperature information from a composite of soil and plant temperatures  
3 measured by a sensor scanning perpendicular to crop rows. He found that  
4 if a critical scan angle (determined from reflectance measurements) was  
5 exceeded, the temperature obtained from the scanner was that of sunlit  
6 vegetation. He also found that the extraction process was difficult  
7 for canopies having low percent cover.

8 We evaluated relationships among percent cover, soil and crop  
9 temperature, and radiometric measurements of canopy temperature, and  
10 assessed the potential for extracting canopy temperature using  
11 temperature measurements from a nadir-viewing radiometer. We also  
12 assessed the errors associated with neglecting emissivity and sky  
13 radiance corrections.

#### 14 MATERIALS AND METHODS

15 Experiments were conducted on a 25m x 300m field of Volga loam  
16 [fine-loamy over sandy or sandy-skeletal, mixed (calcareous), frigid,  
17 Cumulic Haplaquoll] at the South Dakota State University Agricultural  
18 Engineering Research Farm located 8 km south of Brookings, South  
19 Dakota. Larker barley [Hordeum vulgare L.] was planted in the field  
20 at 15-cm row spacings (north-south rows) at a population of 2.5  
21 million plants ha.<sup>-1</sup> The barley was not irrigated. Surface roughness  
22 of the soil was minimal.

23 Surface soil temperatures (approximately 1 mm below the soil  
24 surface) were measured with copper-constantan thermocouples at two  
25 locations (A and B) within the field. For each location, three  
26 thermocouples were wired in parallel to obtain an average measurement  
27 of shaded and sunlit soil which approximated surface temperature.

1 Composite temperatures consisting of contributions from the soil surface  
2 and the barley were measured at 1330 Local Standard Time (LST) on clear  
3 days with a precision radiation thermometer (Model PRT-5, Barnes  
4 Engineering Co.)<sup>3/</sup> at a vertical position (zero degree look angle  
5 measured from nadir) at a height of 2 m above the canopy. The  
6 temperature resolution of the 20° field of view PRT was  $\pm 0.5$  C in the  
7 8-14  $\mu$ m wavelength interval. Canopy temperatures were measured with the  
8 PRT-5 at a height of 1 m above the canopy and a look angle of 30° from  
9 the horizontal (Millard et al., 1980) pointing to the east and the west  
10 (perpendicular to row direction). At that angle, direction, and canopy  
11 cover, minimal radiance contributions from the soil were detected by the  
12 PRT-5. Canopy temperatures were corrected for emissivity and sky  
13 radiance.

14 Emissivities of the canopy at full cover were measured using a  
15 procedure similar to that described by Fuchs and Tanner (1966). We used  
16 a painted aluminum plate with an emissivity of 0.52 rather than an  
17 anodized plate to determine sky radiance (Blad and Rosenberg, 1976).  
18 Soil emissivities were measured on a bare soil plot adjacent to the  
19 barley field.

20 Soil water contents (0 to 4-cm layer) for each location were  
21 determined gravimetrically on soil samples collected at the time of the  
22 temperature measurements. Percent cover was determined using 35 mm  
23 color infrared slides of the canopy (photographed from a vertical  
24 position approximately 1 m above the canopy) projected on a random dot  
25 grid. Figure 1 shows seasonal trends in percent cover of the barley  
26 canopy.

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27 <sup>3/</sup> Mention of a trade name does not imply endorsement by S.D. State Univ.

## RESULTS AND DISCUSSION

In the discussion that follows composite temperature refers to apparent temperatures measured by the nadir-viewing PRT-5. Canopy temperature refers to temperature measured by the PRT-5 at a 30° angle from the horizontal.

During the investigation, composite temperatures were 0.5 to 11.5 C higher and surface soil temperatures 1.5 to 20 C higher than canopy temperatures (Fig. 2). As expected, differences between composite and canopy temperature decreased as canopy cover increased and less emitted radiation from the warm soil background was detected by the radiometer. The correlation between composite and canopy temperature was non-significant ( $r = 0.41$ ).

Millard et al. (1980) found that errors from assuming nadir-viewing thermal scanner measurements represented actual canopy temperature were a linear function of canopy cover. We found a highly significant linear relationship ( $r^2 = 0.52$ ) between the composite-canopy temperature difference and percent cover (Fig. 3). However, the considerable scatter in our data suggests that it may not be possible to assess errors in determining canopy temperature using only canopy cover information as Millard et al. (1980) suggested.

We assumed the longwave radiation flux from a canopy and the soil background could be approximated by the relationship

$$R = f_c \epsilon_c \sigma T_c^4 + (1-f_c) \epsilon_s \sigma T_s^4 + f_c (1-\epsilon_c) B^* + (1-f_c) (1-\epsilon_s) B^* \quad [1]$$

where  $R$  ( $W m^{-2}$ ) is longwave flux,  $f_c$  is percent cover

expressed as a fraction,  $\epsilon_c$  is canopy emissivity,  $\epsilon_s$  is soil emissivity,  $T_c$  (K) is canopy temperature,  $T_s$  (K) is surface soil temperature,  $\sigma$  ( $5.67 \times 10^{-8} W m^{-2} K^{-4}$ ) is the Stefan-Boltzmann constant, and  $B^*$  ( $W m^{-2}$ ) is

1 longwave sky radiance. The first two terms on the right-hand side of  
 2 equation [1] represent longwave radiation emitted from the canopy and  
 3 exposed soil background, respectively. The last two terms represent sky  
 4 radiance reflected from the canopy and exposed soil background,  
 5 respectively. The complex relationship of emitted and reflected  
 6 radiation between the canopy and the soil is ignored in equation [1].  
 7 Equation [1] also does not partition fractions of shaded and sunlit  
 8 leaves, or fractions of exposed soil background which are shaded and  
 9 sunlit. Canopy temperature can be expressed by rearranging equation [1]  
 10 to give

$$11 \quad T_c = \left[ \frac{R - (1-f_c)\epsilon_s T_s^4 - f_c(1-\epsilon_c)B^* - (1-f_c)(1-\epsilon_s)B^*}{f_c \epsilon_c \sigma} \right]^{1/4} \quad [2]$$

13 We compared observed values of  $T_c$  with values predicted using  
 14 equation [2] and measured values of  $f_c$ ,  $T_s$  and  $B^*$  (Fig. 4).  $R$  was  
 15 calculated from measurements of composite temperature using the  
 16 relationship  $R = \sigma T_{\text{comp}}^4$  where  $T_{\text{comp}}$  is composite temperature. A  
 17 measured value of 0.98 was used for  $\epsilon_c$ . Soil emissivity varied with  
 18 water content as shown in Fig. 5. Linear regression analysis of  
 19 predicted versus observed canopy temperature yielded a slope of 1.04, an  
 20 intercept of -0.53, and a  $r^2$  of 0.88. Differences of observed from  
 21 predicted values ranged from -1.84 to +2.50 C. The prediction accuracy  
 22 of equation [2] was independent of canopy cover. The correlation  
 23 between predicted minus observed canopy temperature and percent  
 24 cover was 0.26 (non-significant).

25 Many investigators have discussed the importance of correcting  
 26 radiometric data for emissivity variations. Bartholic et al. (1972)  
 27 reported temperature errors ranging from 1.9 C for bare, dry soil to 0.8



1 for cotton which arose from assuming an emissivity of 1. Jackson et al.  
2 (1977) reported a nearly constant error of 1.7 C for wheat temperature  
3 by not correcting for emissivity. Similarly, Sutherland and Bartholic  
4 (1977) found that assuming an emissivity of 1 produced errors on the  
5 order of 1.0 C for complete canopies.

6 Figure 6 compares observed canopy temperatures with values  
7 predicted using emissivities of 1 for the soil and canopy in equation  
8 [2]. Linear regression analysis of predicted versus observed canopy  
9 temperatures yielded a slope of 1.14, an intercept of -5.08, and a  $r^2$   
10 of 0.76. Differences of observed from predicted values ranged from  
11 -6.43 to +1.70 C.

12 Prediction accuracy when values of 1 were used for  $\epsilon_c$  and  $\epsilon_s$  was a  
13 function of canopy cover as shown in Fig. 7. Greatest errors occurred  
14 at low percent cover when radiance contributions from the soil were  
15 greatest. The magnitude of the emissivity correction depends not only  
16 on canopy cover, but also on soil type and water content. Emissivities  
17 ranging from 0.90 to 0.93 for dry sand to 0.98 to 0.99 for loamy soils  
18 have been reported (Sellers, 1972; Sutherland and Bartholic, 1977;  
19 Tyalor, 1979).

20 Figure 8 compares observed canopy temperatures with values  
21 predicted using measured emissivities in equation [2], but neglecting  
22 the reflected sky radiance components. Differences of observed from  
23 predicted values ranged from 0.8 to 10.7 C. Regression analysis of  
24 predicted versus observed canopy temperatures gave a slope of 0.66, an  
25 intercept of 7.74 and a  $r^2$  of 0.66.

26 Prediction accuracy, when neglecting the  $B^*$  terms, changed with  
27 canopy cover, with greatest errors occurring at low cover (Fig. 7). The

1 sum of the reflected B\* components ranged from  $13.2 \text{ W m}^{-2}$  at 23% cover  
2 to  $5.6 \text{ W m}^{-2}$  at 90% cover.

3        This study has shown that accurate estimates of canopy temperatures  
4 at incomplete cover are possible from nadir-viewing radiometers if  
5 appropriate considerations are given to soil background radiance,  
6 emissivity and sky radiance. Remote sensing evaluations of canopy cover  
7 have been demonstrated (Heilman et al., 1977; Kanemasu et al., 1977;  
8 Tucker et al., 1978; Jackson et al., 1979), and sky radiance can be  
9 estimated from prevailing sky conditions (Soer, 1980). Estimating the  
10 radiance contribution from the soil background remains a difficult  
11 problem. Models have been developed for estimating surface and near  
12 surface soil temperature (Behroozi-Lar et al., 1975; Pratt and Elyett,  
13 1979; Meyer et al., 1975) and they can potentially be extended to crop  
14 canopies. All three factors must be included in models to accurately  
15 assess canopy temperature at low canopy cover.

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## LIST OF FIGURES

Fig. 1. Seasonal variations in percent cover of the barley canopy.

Jointing and heading occurred on 16 June and 19 July, respectively.

Fig. 2. Comparison of composite temperatures with canopy temperature (A), and surface soil temperature (B) at 1330 LST.

Fig. 3. Composite-canopy temperature difference as a function of percent cover.

Fig. 4. Comparison of predicted and observed canopy temperatures.

Canopy temperatures were predicted using equation [2].

Fig. 5. Relationship between measured soil emissivity and volumetric water content in the 0-4 cm layer.

Fig. 6. Comparison of predicted canopy temperatures, using values of 1 for  $\epsilon_c$  and  $\epsilon_s$  in equation [2], with observed values.

Fig. 7. Predicted minus observed canopy temperatures as a function of percent cover when values of 1 were used for  $\epsilon_c$  and  $\epsilon_s$  (circles); and when measured values of  $\epsilon_c$  and  $\epsilon_s$  were used, but sky radiance terms were neglected (triangles).

Fig. 8. Comparison of predicted and observed canopy temperatures when measured emissivities were used in equation [2], but reflected sky radiance terms were neglected.

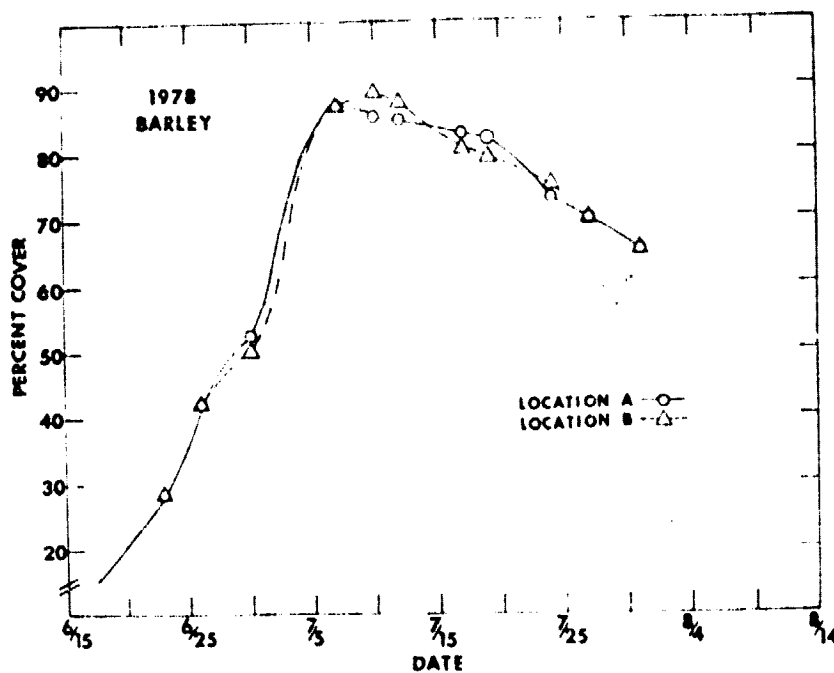


Fig. 1. Seasonal variations in percent cover of the barley canopy. Jointing and heading occurred on 16 June and 19 July, respectively.

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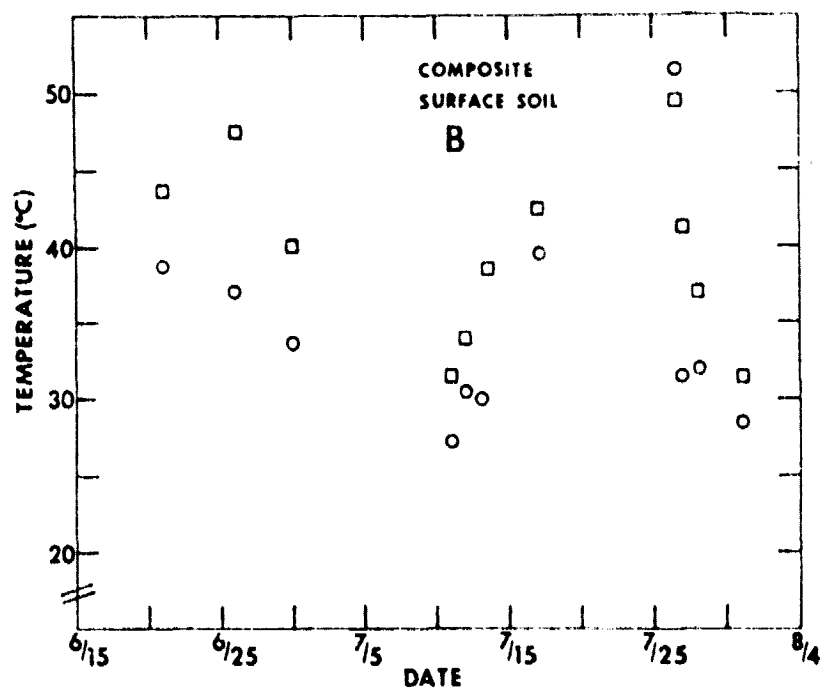
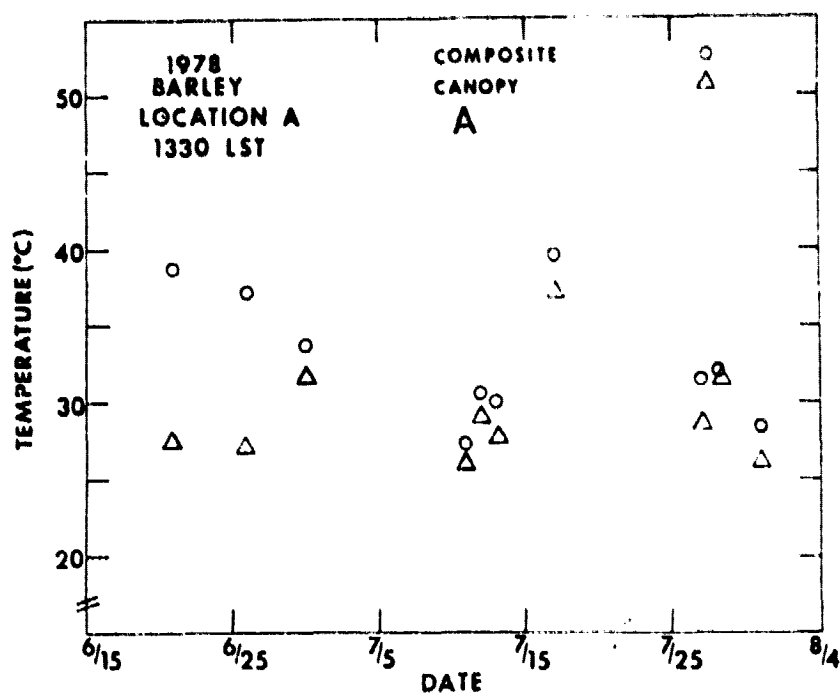


Fig. 2 Comparison of composite temperatures with canopy temperature (A), and surface soil temperature (B) at 1330 LST.



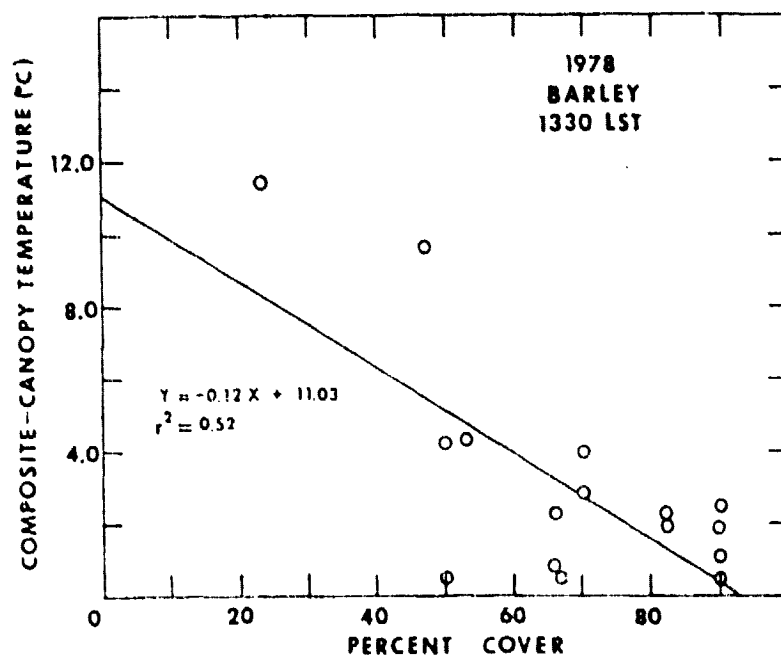


Fig. 3. Composite-canopy temperature difference as a function of percent cover.

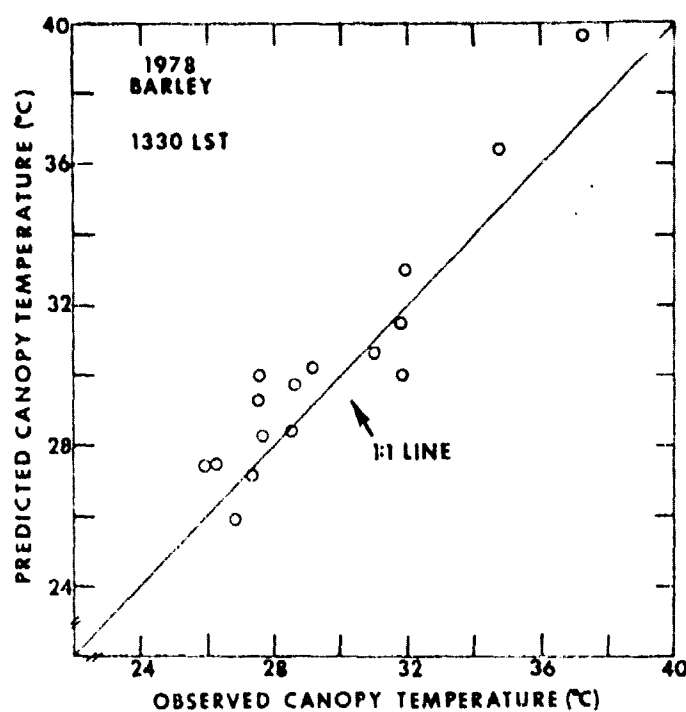


Fig. 4. Comparison of predicted and observed canopy temperatures. Canopy temperatures were predicted using equation [2].

A. Problems

None

B. Accomplishments

Analyses of all data are continuing.

C. Significant Results

Additional dates of HCMM data have been included in the analyses documented in the March 1980 progress report (SDSU-RSI-80-03). Addition of the new data confirmed that HCMM radiometric temperatures corrected for vegetation difference were significantly correlated to both near-surface soil moisture and depth to groundwater.

D. Publications

"Remote sensing of canopy temperature at incomplete cover" to be submitted to Agronomy Journal (see Appendix A).

E. Recommendations

None

F. Funds Expended

\$90,596.43

APPENDIX A

Remote Sensing of Canopy Temperature at Incomplete Cover

(Submitted to Agronomy Journal)

1 REMOTE SENSING OF CANOPY TEMPERATURE

2 AT INCOMPLETE COVER<sup>1/</sup>

3 J.L. Heilman, W.E. Heilman, and D.G. Moore<sup>2/</sup>

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21 \_\_\_\_\_  
22 <sup>1/</sup>Contribution No. SDSU-RSI-J-80-05 from the Remote Sensing Institute,  
23 South Dakota State University, Brookings, SD 57007. Research  
24 supported in part by NASA under contract no. NAS5-24206, and the  
25 State of South Dakota.

26 <sup>2/</sup>Research Soil Physicist, Research Assistant, and Assistant Director,  
27 respectively.

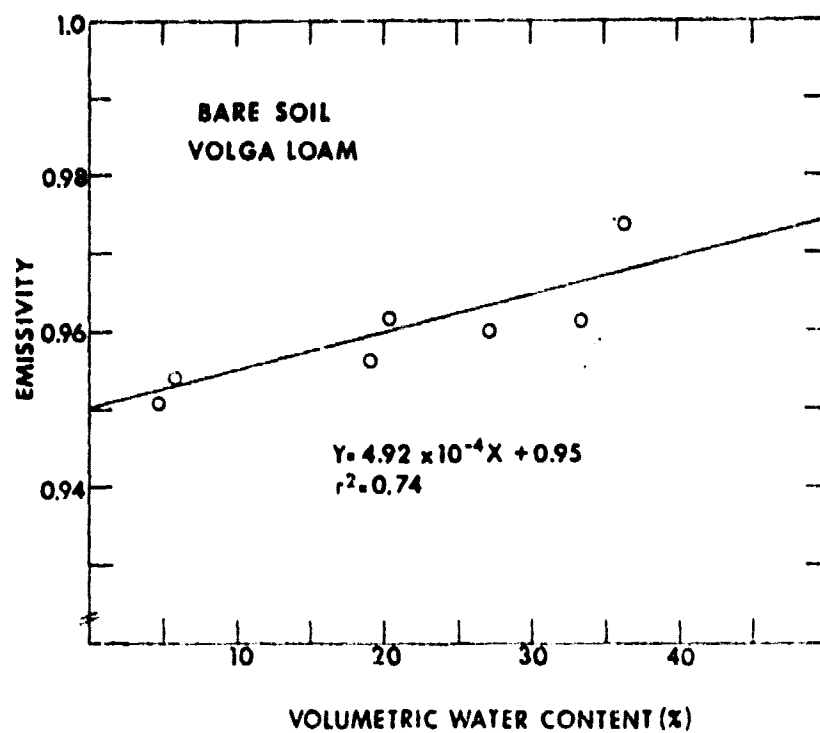


Fig. 5. Relationship between measured soil emissivity and volumetric water content in the 0-4 cm layer.

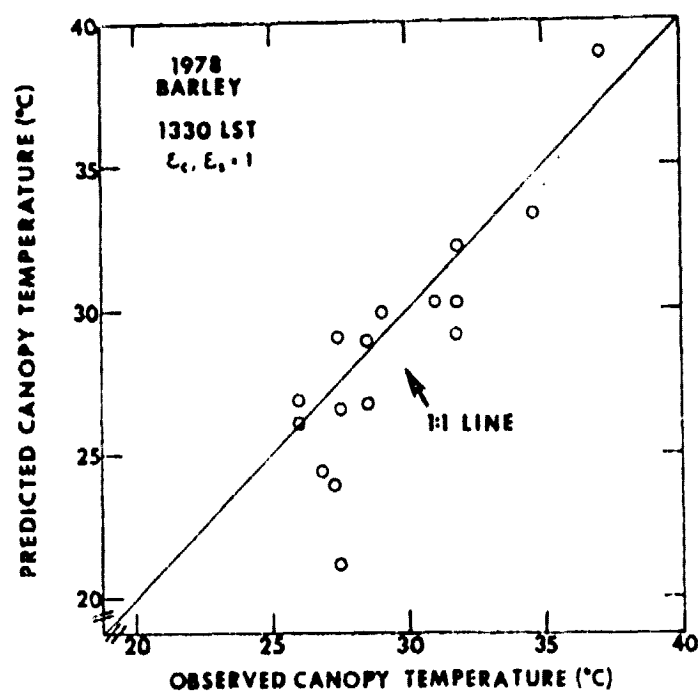


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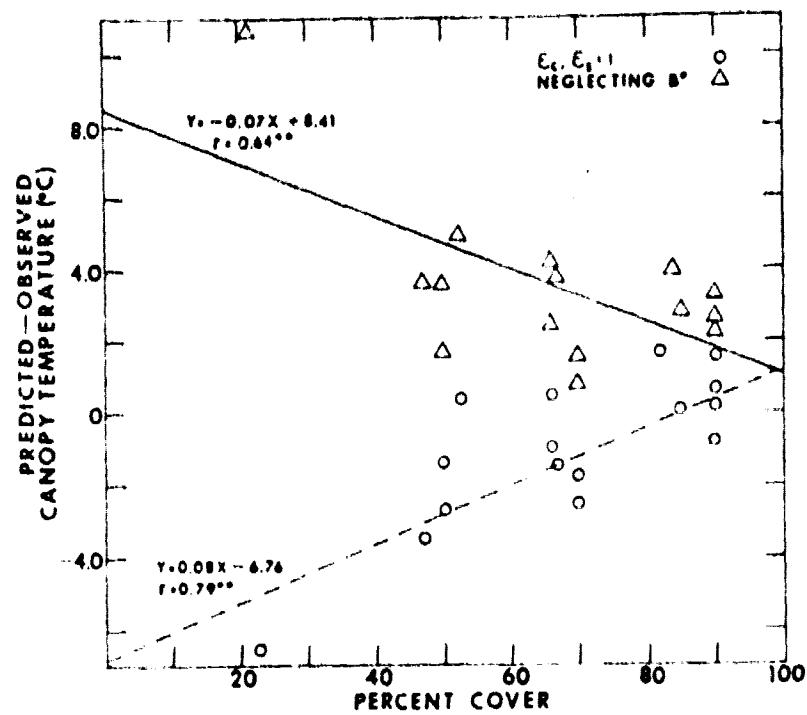


Fig. 7. Predicted minus observed canopy temperatures as a function of percent cover when values of 1 were used for  $\epsilon_c$  and  $\epsilon_s$  (circles); and when measured values of  $\epsilon_c$  and  $\epsilon_s$  were used, but sky radiance terms were neglected (triangles).



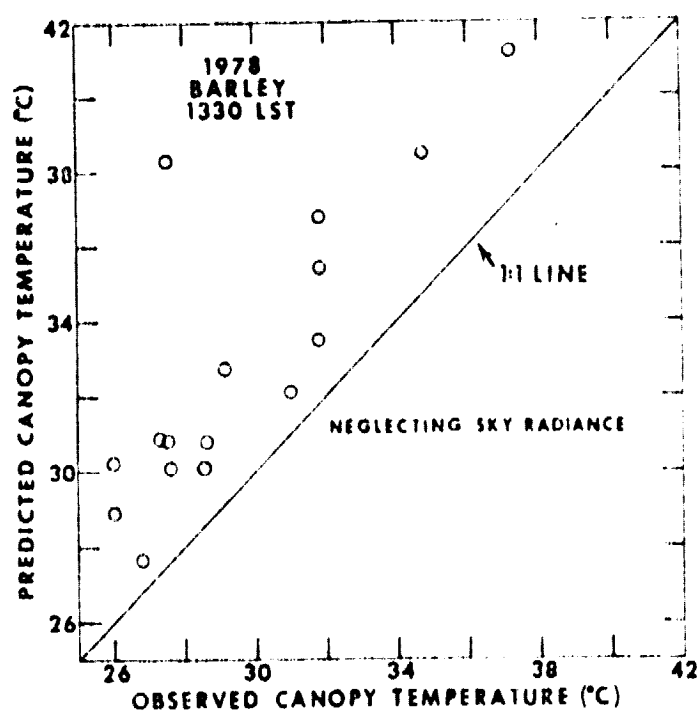


Fig. 8. Comparison of predicted and observed canopy temperatures when measured emissivities were used in equation [2], but reflected sky radiance terms were neglected.